CERTAIN TYPES OF STREAM VALLEYS AND THEIR MEANING

JOHN LYON RICH
University of Illinois, Urbana, Ill.

A recent study of the "thalwegs" or immediate valleys of a number of streams, with particular reference to their ground-plan and their form as revealed in cross-section, has brought to my attention a wide difference in form of valleys produced by different streams and even by a single stream in different parts of its course. A subsequent failure to find in the literature any approximately complete explanation of these differences in form leads me to attempt the following analysis of the work of a river in carving its valley, in the hope that it will lead to a clearer understanding of the meaning of these marked morphological differences and will pave the way for the use of these distinctive valley forms as criteria for the interpretation of the physical history of a region where they occur.

An examination of a large number of valleys, as delineated on the contour maps published by the United States Geological Survey and by the French and German Surveys, led to their classification under three types which seem fundamental. For each type there is a further series of stages marking the development of the valley from its initial to its final form. For the three types I suggest the following names:

1. The Open Valley.
2. The Intrenched Meander Valley.
3. The In-grown Meander Valley.

The *Open Valley* is one which is either straight, as valleys go, or winding in broad, open curves. The valley sides are relatively straight and may be smoothly trimmed. The stream swings from side to side in broad, open curves which, except in the very earliest stages, do not necessarily correspond with the curves of the valley as a whole.

The *Intrenched Meander Valley*[1] is one whose stream, having inherited a meandering course from a previous erosion cycle, has sunk itself into the rock with little modification of its original course.

The *In-grown Meander Valley* is one whose stream, which may or may not have inherited a meandering course from a previous cycle, has developed such a course or expanded its inherited one as it cut down. Thus, as the stream sunk its channel lower and lower into the bed-rock, the meanders were continually *growing* or expanding. The term "in-grown" has been chosen to express this idea.

Three valleys illustrating the above types have been selected from the United States Topographic Atlas. A brief description of each should bring out the most essential characteristics of its type:

1. Typical of the first group, the *open valley*, is that of the Kanawha River as depicted on the Charleston (W.Va.) special sheet; U.S. Geol. Survey (see Fig. 1). The valley of Elk River, entering the Kanawha at Charleston, also illustrates this type as developed by a smaller stream.

The "thalweg," or immediate trough of the Kanawha River, is sunk some six or seven hundred feet below the general level of the neighboring upland, which it traverses in broad, open curves. The valley bottom is flat and about two-thirds of a mile wide, or about six times as wide as the stream. The sides are steep and trimmed to remarkable regularity—being, in fact, practically parallel. There is a slight tendency to greater steepness of the concave bank on the sharper bends. In this open, flat-bottomed valley the stream swings in broad, free curves, now hugging one bank, now the other. A space of something like six miles intervenes between successive points of impingement against the same bank. The curves of the stream in its swinging do not everywhere correspond with those of the valley trough.

The flat bottom, so conspicuous in the valley of the Kanawha, is not considered an essential feature of the open valley. A non-meandering valley with a V-shaped cross-section would, in the sense

[1] The term "incised meander" has, apparently, been used synonymously with intrenched meander in previous writings. Would it not be well to use "incised meander" as a generic term covering both the above-described cases, and to restrict the meaning of intrenched meander as indicated above?

in which the writer proposes to apply the term, be as truly an "open valley" as the flat-bottomed one described above.

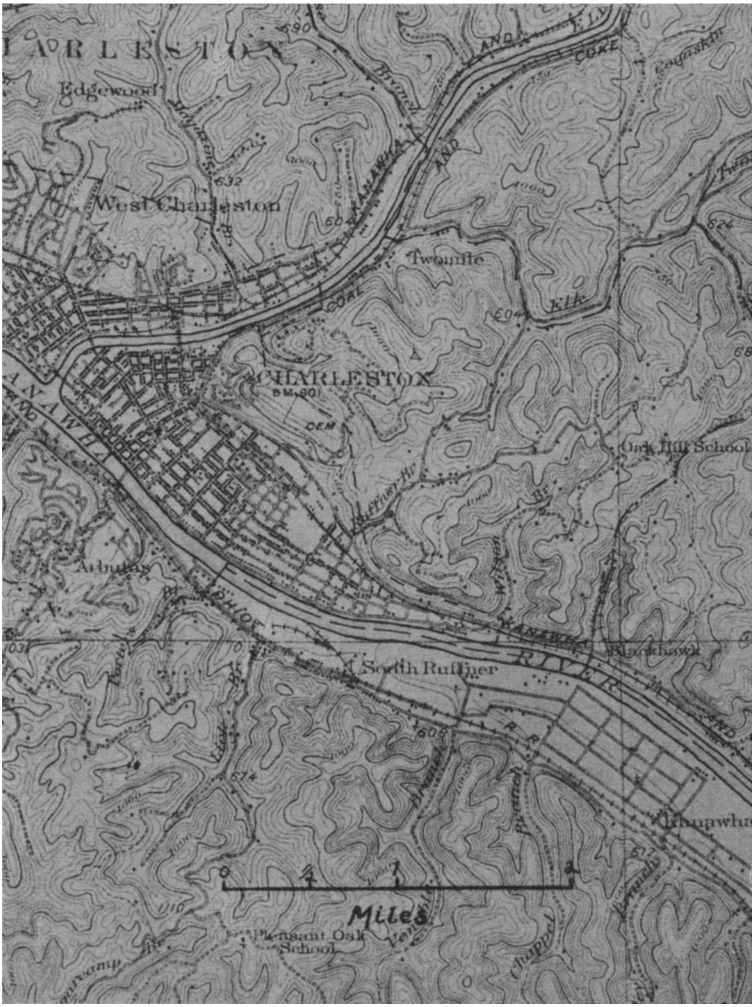

FIG. 1.—Part of the Charleston (W.Va.) special topographic sheet showing typical "open" valleys. Contour interval 20 feet.

2. The second type, or *intrenched meander valley*, is finely illustrated by that of the Kentucky River and its tributary the Dix,

as shown on the Harrodsburg (Ky.) topographic sheet. A part of this is reproduced as Fig. 2.

FIG. 2.—Part of Harrodsburg (Ky.) topographic sheet showing typical intrenched meander valleys. Contour interval 50 feet.

These rivers follow remarkably sinuous meandering courses. The meanders, however, are sunk sharply into the upland, and

show no evidence of having been widened appreciably during the time of their incision. The windings of the valley correspond with

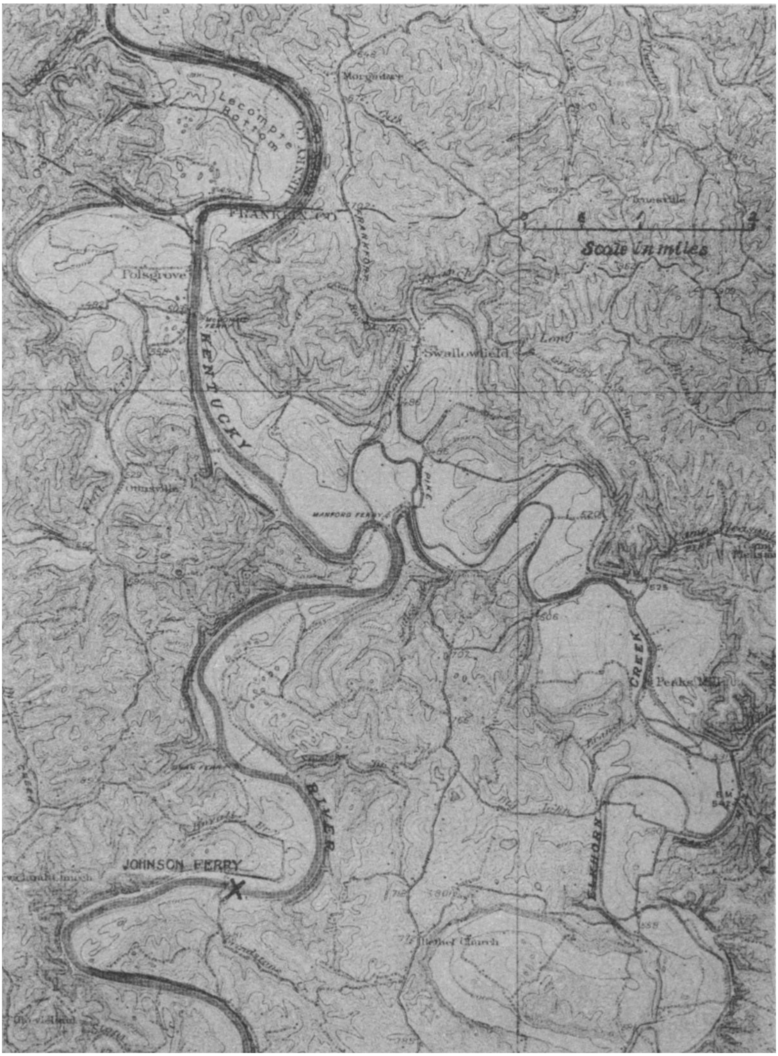

FIG. 3.—Part of Lockport (Ky.) topographic sheet showing typical in-grown meander valleys. Contour interval 20 feet.

those of the stream. Lack of flats along the stream indicates that incision is still in progress.

It is especially characteristic of this type that the portion of the upland between the meander loops keeps its full height and flat surface almost to the inside end of the loops. The valley, in cross-section through the end of one of the loops in a direction transverse to the general direction of the stream, is practically symmetrical. There is a slight tendency to the development of "slip-off slopes" and undercut bluffs, but it is subordinate.

3. The *in-grown meander valley* is well shown on many of the United States topographic maps. One of the most beautiful which has come to my notice is portrayed on the southern part of the Lockport (Ky.) sheet, where the valleys of the Kentucky River and Elkhorn Creek display with great clearness the characteristics of the type (Fig. 3). The concave and the down-valley banks are marked by steep bluffs, while on the insides of the loops are well-marked slip-off slopes descending gently to the river. This characteristic feature is clearly shown on the inside of the loop just above Johnson Ferry (**X** on the map, Fig. 3).

Such a valley presents clear evidence that whatever may have been the course of the river in a previous cycle, the meanders have been much widened and enlarged during the present cycle.

All three of the valleys described above are the products of comparatively young and decidedly vigorous streams. All three, moreover, are in approximately the same stage of development in the erosion cycle—namely, youth to maturity. All are, or have recently been, degrading streams. We cannot, therefore, ascribe the differences in valley form to differences in the stage of development of the valleys. The differences are more fundamental than that. Nor are we dealing with old-age streams in which the meanders are features of the flood plain. Such old-age streams and valleys may be looked upon as *end products* of the development of any one of the types of valley described above.

Having recognized these distinctive valley types we are confronted with the problem: What conditions determine the type of valley which a stream will develop? A satisfactory solution of that problem calls for a brief review of some of the basic principles of river work.

ANALYSIS OF THE WORK OF A RIVER IN CARVING ITS VALLEY

The development of the immediate valley or thalweg of a river is accomplished mainly by a combination of three well-known processes—vertical down-cutting, lateral cutting, and down-valley migration of the curves or meanders, to which Davis has applied the excellent term "sweep." Of these, vertical cutting, when the conditions are favorable, is much the most rapid, because it has gravity as its direct and powerful ally.

In a normal degrading stream, all three processes are active in shaping the valley, but vertical cutting may be so much more rapid than the others as to mask their effects. When, however, a stream approaches grade and vertical cutting diminishes, one or the other of the two remaining processes advances to prime importance.

Any one of these processes, if dominant, is capable of impressing upon the valley, which it is helping to shape, certain characteristics of form which are distinctive. An acquaintance with these distinctive forms should enable one, on examining a valley, to determine which process took the leading part in its sculpture. If, carrying the analysis back a step farther, we can determine the controlling factors which lead to dominance of a given process, we shall be in a position to read much of the physical history of a region from the form of its valleys.

DISTINCTIVE FORMS ASSOCIATED WITH EACH OF THE THREE VALLEY-CUTTING PROCESSES

Dominant down-cutting implies that a stream is sinking its bed vertically at a greater rate than it is cutting laterally or down-valleyward on the bends. The necessary result of such a process is the development of a *gorge-valley* with narrow bottom, not, as a rule, much wider than the stream at flood, and with sides whose steepness, while usually great, depends largely on the nature of the rock and on the activity of weathering agents. The stream tends to sink itself vertically in whatever course, whether straight or meandering, it may hold at the beginning of down-cutting. Lateral cutting and sweep will modify this original pattern somewhat, but not to the extent of destroying the characteristic gorge form.

Dominant lateral cutting.—The well-known tendency of a stream to swing from side to side of its valley results in very unequal wear on its channel—active under-cutting on the outsides of the bends being accompanied by deposition on the insides.

An inspection of Fig. 5 will make clear that lateral cutting alone, a result of the force due to inertia, should result in *symmetrical* enlargement of the meanders without their displacement. The resulting topographic feature would be the symmetrical undercut bluff or meander scaur combined, if the stream were cutting down meanwhile, with symmetrical slip-off slopes. A thalweg, therefore, shaped by dominant lateral cutting should present a pronounced scalloped outline—the greater the dominance of lateral cutting the more symmetrical and the more nearly circular the scallops. That we do not find these symmetrical forms in normal valleys is sufficient evidence that with lateral cutting there is combined another process which destroys the symmetry. That process is *sweep*.

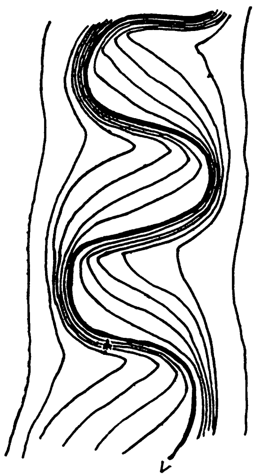

FIG. 4.—Contour sketch showing typical features of an in-grown meander valley, and the effect of sweep in producing assymmetry. Note the unsymmetrical necks of land on the insides of the loops; the sharp undercut bluffs on the outside and down-valley sides of the bends, and the gently inclined slip-off slopes opposite.

Dominant sweep.—The down-valley migration, or sweep, of meanders brings the stream successively over all parts of its valley flat. Any obstructions in the valley, opposing the orderly march of the meanders across and down the valley, is attacked. Thus the whole tendency of sweep is toward a *clearing-out* of the valley by the removal of spurs or other obstructions. It follows, therefore that, where sweep dominates, only the open type of valley (type I above) is "stable." In the case of a valley of the meandering type, the tendency of the meanders to sweep down-valley leads to more active erosion on the down-valley sides of the meander bends than on the up-valley sides. This results in asymmetry of both

undercut bluffs and slip-off slopes with resulting forms like those illustrated in contours in Fig. 4.[1]

Combinations of processes.—As already stated, all three of the above processes are normally in operation at the same time along a stream valley. The analysis of the form produced when any one is dominant is a necessary preliminary to an understanding of the more complex forms resulting when two or more of these processes act in combination. Where down-cutting is vigorous the effects of the other two are, as a rule, masked to a greater or less degree. A gorge-like valley is the result. When, in the history of a stream, down-cutting ceases or becomes very slow, lateral cutting continues to widen the valley[2] while sweep tends to clear it out if it is not already relatively straight. Once a valley assumes the open form, whether as a result of initial conditions or as a consequence of the clearing effect of sweep, the constant down-valley procession of meanders tends, throughout the remainder of the cycle, to maintain this form by shifting continually the locus of attack of the stream, and to produce a valley with fairly uniform width and with relatively straight walls.

Between the stage marked by predominant down-cutting and that marked by predominant sweep there must be an intermediate stage when sweep, down-cutting, and lateral cutting bear such a relation to one another that whatever width of meander is gained by the stream in its lateral cutting is retained because of the contemporaneous down-cutting, while the spurs between the meanders, with their characteristic slip-off slopes, are not cleared out by sweep. In valleys developed under such conditions, the slip-off slopes would be conspicuous and the undercut bluffs well developed. The form would be that of the in-grown meander valley (type 3 above). Sweep, in this case, would be subordinate because, as will be explained more fully in a subsequent paragraph, in the interval between the sweep of successive meanders past a given point,

[1] W. M. Davis, "Incised Meandering Valleys," *Bull. Geog. Soc. Philadelphia*, IV (1906), 182–92.

[2] A. Penck, *Morphologie der Erdoberfläche*, II. Buch, I. Abschnitt, S. 350: "Langsame Vertiefung ist das Erforderniss zum gleichseitigen Verschieben der Flussbetten. Sobald erstere rasch geschieht und auch letztere erfolgt, so wird eine ungeheuere Trummermasse dem Flusse zugeführt werden, die er nicht zu bewältigen vermag."

the stream would have lowered its bed so that each succeeding meander in its sweep would be opposed by rock.

CONTROLLING FACTORS DETERMINING THE DOMINANT PROCESS

Down-cutting will dominate whenever a stream finds its bed well above its local profile of equilibrium. After a stream reaches grade it may still lower its bed as the general level of the country is lowered, but the process must be gradual—too gradual for the continued dominance of down-cutting over lateral cutting or sweep.

Lateral cutting.—The tendency toward lateral cutting, which, it appears, is dependent upon a balance between two opposing forces[1]—(1) that due to inertia, tending to displace the thread of fastest current tangentially from one bank to the other, thereby favoring lateral cutting, and (2) the down-stream component of gravity, tending to make the current follow parallel to the walls of the channel—is controlled largely by the gradient of the stream, which determines the latter of these two forces. The lower the gradient the greater the proportion of the stream's energy used in lateral as distinguished from down-valleyward corrasion.

Volume also must play a part, for increased volume, by decreasing friction and thereby increasing velocity, would augment the value of the force due to inertia, and would therefore favor lateral cutting.

Sweep, it appears, particularly the ratio of the rate of sweep to that of down-cutting, plays a most fundamental part in determining the form of the valley. It deserves, therefore, a more detailed study.

Three factors suggest themselves as determining the rate of down-valley migration of meanders, or sweep. These are: the gradient of the stream, its volume, and the character of the material against which it impinges at the bends.

The importance of gradient and volume will be apparent from a study of Fig. 5, which illustrates the forces acting in a meandering stream. In a bend such as that shown in the diagram, inertia, if acting alone, would throw the current from *A* diagonally across the channel to *B* in the direction of the tangent to the curve

[1] See Fig. 5.

of the bank at A. If only inertia were acting, the meanders would be enlarged symmetrically; but there are two other factors to be taken into account. These are the down-stream component of gravity and the tendency of the thread of the current to follow the shortest course round the insides of the bends.[1] The former of these acting on a particle of water at any point, X, would tend to make the particle move in a direction X-Y, parallel to the median line of the stream at that point. The latter would tend to lead the current along the inner bank, A-C. The resultant course of the thread of fastest current would be along some line such as A-D, intermediate between A-B and A-C, giving greatest erosion at and below D rather than at B. The current, on account of a combination of the two latter forces, would hug the down-valley bank A-C more closely than would otherwise be the case, while it would draw away from the up-valley bank near B. Thus would the meander migrate down-valley.

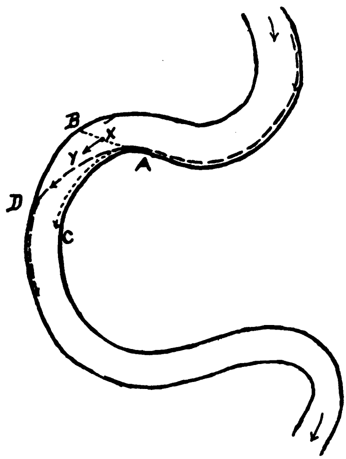

FIG. 5.—Diagram of a stream meander to show the explanation of the down-valley migration or sweep of meanders and the effects of gradient on the forces concerned. The dashed line represents the thread of fastest current; the dotted lines the courses this thread of fastest current would take if the various forces were acting alone. The line from A to B represents its course if inertia alone were active; A to C that if inertia were inoperative.

It is at once evident that an increase in gradient of the stream would increase this tendency to down-valley migration because it would increase the down-valley component of gravity at a greater rate than it would increase the force due to inertia, since the latter, dependent as it is on velocity, would be cut down by friction.

Increase in volume without change in gradient would tend toward greater symmetry and relatively slower down-valley migration, for greater velocity, due to lessened frictional resistance,

[1] J. Thompson, *Proceedings of the Royal Society of London*, XXV (1876), 5–8.

would increase the inertia component without altering either of the other two.

In respect to the third of the factors determining the rate of sweep, it is of course evident that this rate will, other things being equal, depend directly on the resistance of the material against which the stream is working. If this material is the soft alluvium of a flood plain, the meanders will sweep past rapidly; if it is resistant rock they will go much more slowly. If the banks are low, less material must be moved than if they are high, consequently the meanders will tend to move more rapidly.

Where the meanders are intrenched, lateral, vertical, and down-valley erosion will be equally affected by the character of the rock but where a stream is flowing on a flood-plain-floored valley with rock bluffs on the sides, lateral cutting into the valley walls is opposed by rock, while sweep is opposed only by soft flood plain alluvium of moderate thickness. The result must be a relatively rapid down-valley migration of the curves of the river.

Conditions under which sweep becomes dominant.—The ratio between the rate of sweep and that of down-cutting is one of the fundamental factors in determining the form of a valley. Three common conditions lead to dominance of sweep. These are: (1) a stream at grade in a relatively straight valley; (2) a stream which for any reason, for instance a decrease in gradient, has ceased down-cutting altogether; and (3) a stream carrying *coarse material*.

In the first of these cases a stream, having cut down to its profile of equilibrium in a relatively straight valley, still continues to deepen this valley, but only slowly, as the region as a whole becomes lower. The stream swings from side to side in ever-broadening, open curves. The tendency to down-valley migration of these curves is opposed only by the resistance of the thin coating of relatively weak flood-plain material on the valley flat, plus that of the thickness of rock which represents the amount of down-cutting in the interval between the passage of successive meanders. The tendency toward lateral cutting is opposed by the *rock* of the valley walls. The result is that when the stream is turned against the valley side, the flood-plain material on the lower side of the bends

yields rapidly and the locus of attack on the rock of the valley side is shifted down stream before any great impression on the valley walls can be made. A repetition of this process with its constant down-stream migration of the locus of attack must produce relatively straight valley walls.

In a stream of constant volume, as the gradient gradually decreases with advancing age, the tendency to sweep (dependent on the gradient) decreases, while the tendency toward lateral expansion of the meander loops increases (since the latter becomes relatively more effective as the gradient becomes less). The stream, therefore, remains against its rock banks at any given place longer than before with the result that the straight valley wall characteristic of its earlier stages gradually gives way to a series of crescentic scaurs marking the successive points of impingement—the older ones, perhaps, considerably modified by general weathering since their formation.[1]

In the second case, when a stream has ceased down-cutting altogether or has so nearly ceased that the amount of such cutting is at a minimum, down-valley sweep, combined, of course, with lateral cutting, will take first place and will work out its characteristic results whatever may have been the original form of the valley. In valleys of either the intrenched or the in-grown meander type the stream will develop a flat flood plain, first on the up-valley sides of the bends and on the convex banks of the loops; gradually it will cut off any spoon-shaped necks of land between the loops, perhaps producing "rock islands" as a by-product, and finally it will remove all spurs or isolated rock masses.[2]

The third case, streams carrying coarse material, is best illustrated by the small headwater tributaries of many streams, particularly those in regions of resistant rocks. A plentiful load of coarse material means a high gradient, for only a swift stream is "competent" to the coarse débris.[3] The high gradient gives high values to the forces responsible for down-valley sweep while the

[1] This feature is well shown on the Williamstown (N.C.) topographic sheet.

[2] See W. M. Davis, "River Terraces in New England," *Bull. Mus. Comp. Zoöl.*, XXXVIII (1902), 281–346.

[3] Gilbert, *Henry Mountains*, chapter on "Land Sculpture."

heavy load of coarse débris prevents rapid down-cutting. Sweep therefore dominates.

Conditions unfavorable for rapid sweep.—The following conditions are unfavorable for rapid sweep: low gradient, as explained above; relatively rapid down-cutting; and an original meandering course sunk into bed-rock (the latter not, of course, affecting the tendency to sweep, but only its absolute rapidity in a given case).

Under the second of these, relatively rapid down-cutting, the stream is continually cutting deeper into bed-rock and thus constantly increasing the amount of material to be moved by a meander in sweeping down-valley; not only so, but in the interval between the passage of successive meanders, the stream, at a given point has deepened its bed and there is still *rock*, not flood-plain material, to be removed by each succeeding meander as it sweeps down the valley.

In cases where down-cutting is long continued, but slow enough so that lateral cutting is conspicuous, there may result a peculiar type of valley with its bottom section exhibiting fine specimens of in-grown meanders, but with the upper part of its walls relatively straight. Such a condition would be the necessary result of a passage down-valley of a series of meanders during a slow uplift or its equivalent. What may be a valley of this sort is illustrated by the Chaquaqua Canyon as depicted on the Mesa de Maya (Colo.) sheet (Fig. 9).

The influence of load.—A full load of sediment, by occupying all the stream's available energy in its transportation, is an effective check to down-cutting. This does not, however, interfere with the process of sweep on the flood plain, for the sediment derived from cutting on a concave bank may be redeposited on the convex bank next below without in any way increasing the permanent load of the stream. It is a question also if it entirely prevents lateral cutting on the valley walls at the point of impingement of the meander bends. In a fully loaded stream, at any rate, sweep is dominant and the straight-walled valleys are to be expected.

DEDUCTIVE STUDY OF THE EFFECTS OF THE RATE OF UPLIFT OF A DRAINAGE BASIN ON THE FORM OF ITS VALLEYS

We have already seen what a fundamental rôle in the determination of valley form is played by the *rate of down-cutting*. A deductive study of the effects of differing rates of uplift, with their correlated differing rates of down-cutting, on streams of varying characters should enable us to evaluate properly this important factor.

Rapid uplift of a relatively straight stream.—Assume a region of perfectly homogeneous rocks, drained directly to the sea by a master stream and its tributaries. Let the region have advanced to the old-age stage in the erosion cycle, with all the streams thoroughly graded and with the master stream swinging in long, open curves on its way to the sea. Now, considering only the master stream, assume an uplift of the land uniform in amount throughout the drainage area, and so rapid that the stream in its down-cutting cannot keep pace with it. What will be the result?

In the first place, a wave of down-cutting, beginning at the mouth of the stream, will progress up the valley. Since, by assumption, the stream is a large one, down-cutting will be rapid and will greatly outstrip lateral cutting and sweep. The stream will quickly intrench itself in whatever course it happens to be following. Until grade is reached on the cessation of the uplift, deepening of the lower course of the stream will greatly exceed lateral cutting. As soon, however, as grade is attained, lateral swinging and sweep will increase in relative importance. The latter, as explained above, will dominate and the constant downstream procession of more or less open meander loops will widen the valley and at the same time tend to produce relatively straight valley walls. Further widening and further decrease in gradient will, as already explained, result in the scalloping of the bluffs. Finally, as the flood plain comes to exceed the width of the meander belt, the further widening will be more irregular, and the older of the meander scaurs will lose their original sharpness, though not their characteristic ground-plan.

The valley resulting from such a series of events would correspond to our "open valley" (type 1) and the series of stages through

which it would pass in its development ought to be matched in actual valleys subjected to similar conditions.

Rapid uplift of a meandering stream.—Assume all initial conditions the same as before except that the master stream instead of flowing relatively straight, writhes in closely looped meanders along its lower course toward the sea. Assume, as before, a rapid uplift terminating after a moderate interval.

Down-cutting, as before, will greatly exceed lateral cutting and sweep and the stream will intrench itself with little modification into the bed-rock. On the sharper bends the accentuated lateral cutting may succeed in producing under-cut bluffs and slip-off slopes of moderate extent, but as a whole the stream will merely intrench itself in its inherited course. The cross-section of the valley, except at the sharpest bends will approximate symmetry and the upland marking the original plain will extend unbroken into the inside of the meander loops, in sharp contrast to the gently decending slip-off slopes which mark the insides of the bends when the meander has *developed* as uplift proceeds.

As uplift and down-cutting continue, some of the narrowest necks between meanders are likely to be cut off by under-cutting as has happened at the Frying Pan Bend, and as may eventually happen just above Handy's Bend in the Kentucky River (Fig. 2).

Just so long, however, as the gradient of the stream remains so great that down-cutting dominates, will the meanders continue to intrench themselves deeper and deeper, still holding nearly their original courses.

When the uplift ceases, the master stream will quickly cut down to grade. Thereafter deepening will be slow. Lateral cutting combined with sweep will at once advance to the dominant place, and the bottom of the valley will become widened. The outside and down-valley sides of the meander bends will feel the effects of the changed régime first and most strongly; flats will develop; narrow necks like that at Handy's Bend (Fig. 2) will be quickly cut through, making "rock islands" of the cut-off remnants. Down-valley sweep will continue active and will tend to remove, gradually, the spurs and rock islands from the valley and to transform it into a flat-bottomed, crescent-bordered trough. In

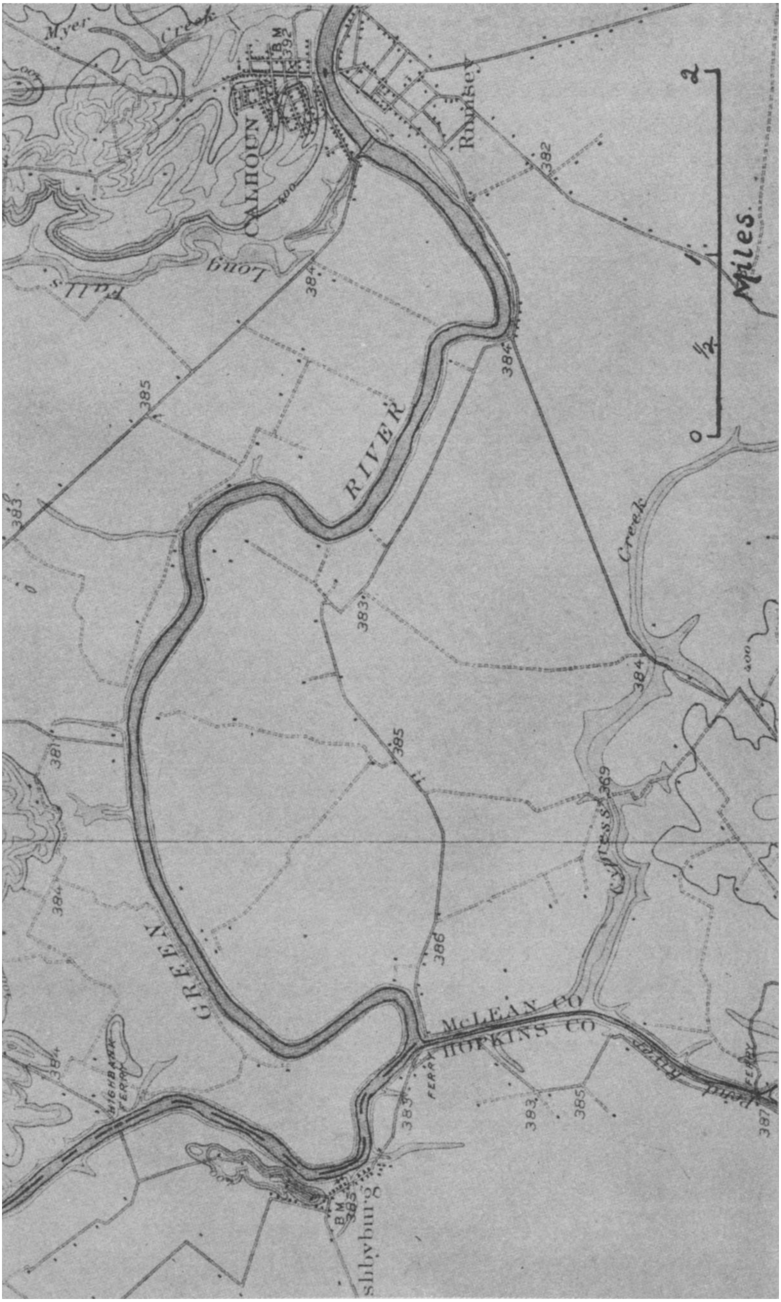

FIG. 6.—The earliest stages of the formation of an intrenched meander valley. Note the almost complete absence of evidence of lateral shifting of the meanders. From the Calhoun (Ky.) topographic sheet. Contour interval 20 feet.

the valleys of swift streams the latter process will be relatively rapid; in those of streams of low gradient, such as the master stream we have postulated, the river may flow for long ages before removing all signs of its former stages.

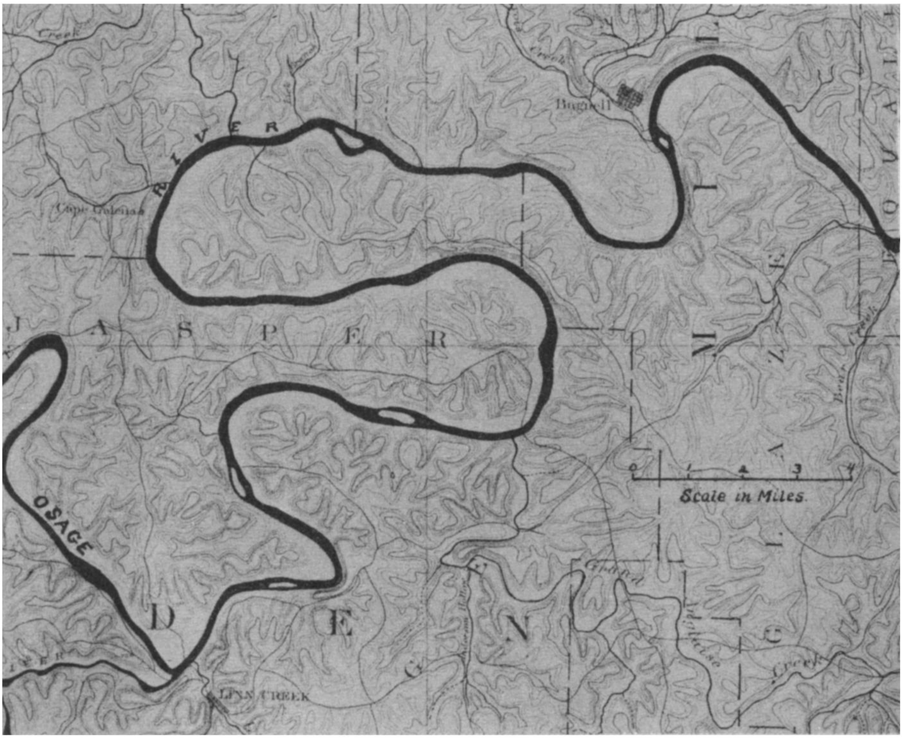

FIG. 7.—An intrenched meander valley in which the stream, having reached grade is beginning to widen the valley. Note that the upland between the loops keeps practically its full height almost to the end. From the Versailles (Mo.) topographic sheet. Contour interval 50 feet.

Examples of streams which show features corresponding to those just deduced are very numerous. For the earliest stage, when intrenchment is just beginning, the Green River in Kentucky (Fig. 6, Calhoun sheet, U.S. Geol. Surv.) is instructive. Here the predominance of down-cutting over lateral cutting in the determina-

tion of the valley form is very evident. Later stages, where the trenching is deeper but where the down-cutting is still active, are shown by such streams as the Kentucky and the Dix (Fig. 2). A still later stage, when grade has been reached and the formation of a flat valley-bottom has begun, is excellently shown on the Versailles (Mo.) sheet of the Geological Survey (Fig. 7). A still more advanced stage in a stream which seems to have had a history somewhat like that just outlined is shown by the Black River on the Oberlin (Ohio) sheet (Fig. 8). At the beginning, the stream, in its lower reaches, seems to have had a distinctly meandering course in which it cut down quickly to grade. It is at present changing the form of its meander bends and opening out its valley on account of a relatively rapid down-valley sweep. At the town of Elyria, where the stream has evidently encountered rock of considerable resistance, it is still cutting down and holds its original meandering course only slightly modified. The valley here is a typical intrenched meander in its youthful stage of development. Further down, in the softer rocks, a more advanced stage has been reached.

Slow uplift of a straight stream.—The results of another type of uplift may be deduced by assuming, as before, an ideal drainage system with the stream flowing in broad, open curves, to be subjected to an uplift so slow and continuous that the stream, while forced to continued down-cutting, is, nevertheless, able to maintain itself continuously near grade.

Under such conditions lateral cutting will assume an important rôle from the very first, and the stream, though its original course may have been comparatively straight, will come to swing in ever-broadening curves. Continued slow lowering of the stream bed will insure the retention of all width of meander gained by lateral cutting. Sweep will, for reasons already set forth—namely low gradient and continuous cutting in rock—take a subordinate place and will not hinder the further development of the meanders in the bed-rock. As the process continues the stream will sink its bed deeper and deeper into the rock; the meanders will become wider and wider, and the form of the resulting valley will be characteristic—the outsides of the meander bends marked by steep undercut bluffs and the insides by more or less gently inclined

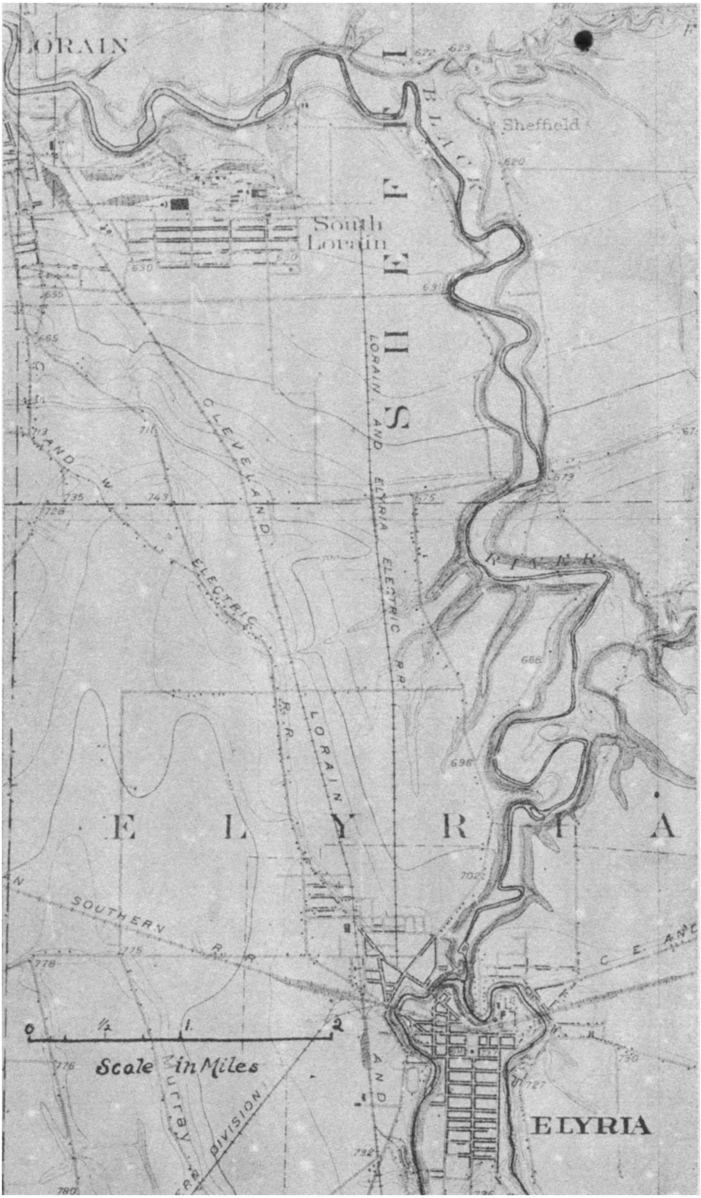

FIG. 8.—Part of the Oberlin (Ohio) topographic sheet, showing a meandering stream of the intrenched type in two different stages of development in different parts of its course. At Elyria it is in the earliest stage of intrenchment; farther down, grade has been reached and sweep is clearing out the valley.

slip-off slopes. Sweep will lead to asymmetry of the necks of land between the loops.[1] In time, if the uplift is continued, a single meander may sweep more than its width down stream, but before the next one arrives the stream bed will have been so lowered that the characteristic valley form will still be preserved. In time cut-offs may develop in solid rock. As uplift continues and the valley becomes deeper, the amount of material to be removed by lateral cutting, or as a result of lateral cutting, will become so great that further increase in the width of the meander belt may be checked. The valley form may then approximate that shown by the Chaquaqua Canyon, Mesa de Maya sheet, Colo. (Fig. 9).

FIG. 9.—A deep valley of the in-grown meander type at the bottom; upper walls noncommittal. From the Mesa de Maya sheet, Colorado.

The reader has, doubtless, ere this discovered the correspondence between these deduced consequences and the features of the ingrown meander type of valley as described above (see also Fig. 3).

After such a slow uplift, with its consequences as just described, has progressed until the stream is incised to a considerable depth below its

[1] W. M. Davis, "Incised Meandering Valleys," *Bull. Geog. Soc. Philadelphia*, IV (1906), 182–92.

original level, what will be the consequences of a cessation of uplift?

The stream, which as we have assumed has kept an approximately graded condition throughout the uplift, will soon cease active down-cutting. Lateral cutting and sweep will, however, continue. A flat flood-plain will begin to develop. All meanders will be pushed down stream, some probably being cut off in the process, leaving rock islands standing isolated on the flats. The tell-tale slip-off slopes and undercut bluffs might, nevertheless, remain in protected spots, and, at least until the new régime became far advanced, would tell the story of the mode of development of the valley, and, incidentally, of the slow and continuous character of the down-cutting. Should the land remain long enough at one level all traces of the undercut bluffs and slip-off slopes would finally be obliterated, and the stream would swing in its meanders across a flat, open flood plain bordered by meander-scalloped valley walls, or bluffs.

Thus we see that the *end product* in this case is similar to that in the others and that the distinctive valley types are characteristic only of the youthful and mature stages of development, while all tend to become alike in the old age stage.

Slow uplift of a meandering stream.—If, with initial conditions as in the last case, we assume, instead of a straight stream, a meandering one with uplift slow enough to keep the master stream cutting down, but never to its full capacity, we should expect lateral cutting, as before, to play a relatively important part from the first. The original meanders would increase in width as they intrenched themselves into the rock. Cut-offs would probably occur. The form of the valley would be that of the *in-grown meander valley* with undercut bluffs on the outsides of the meander bends, or concave banks, and slip-off slopes on the insides or convex banks. There would probably, however, be some of the features of the intrenched meander such as the flat upland between the original meander bends. In the earlier stages of the development of such a valley it might be possible to determine definitely whether the original stream was meandering before the uplift by noting whether or not slip-off slopes

occupy the greater part of the width of the necks of land between the loops.[1]

Conclusions from deductive study.—From the foregoing considerations it becomes apparent that a *slow* uplift, of such a master stream, unless it be so slow that sweep dominates, will tend toward the formation of the *in-grown* type of meander, whether or not the stream meandered widely in the cycle preceding the uplift, and that a *rapid* uplift will result in the intrenchment of the stream in whatever course it may happen to be holding at the time. If this original course happens to be relatively straight, a valley of the open type will develop; if it is meandering, the meanders will be intrenched but will present characteristics sufficient to distinguish them from the *in-grown* meanders resulting from *slow* uplift.

It appears also—and this fact should be emphasized—that, for each of the hypothetical cases studied, the form of the valley goes through a definite and characteristic evolution as it advances in the erosion cycle, but that the end product, namely the open valley, wider than the meander belt and with meander-scalloped sides, is the same in all cases.

New terms might, perhaps with advantage, be invented to designate the different stages in this evolution, or it might, perhaps, be wise to apply the familiar, though somewhat overworked terms, "youthful," "mature," and "old." If this were done "youth" might be made to cover the period up to the time when active down-cutting ceases; "maturity" the period from the latter until wide, meander-scalloped flood plains develop and until the spurs of incised meanders have been cleared away by sweep, and "old age" the remainder of the cycle.

Significance of uplift.—In the preceding discussion we have assumed rapid or slow uplift of the basin of a master stream flowing directly to the sea. We concluded that rapid uplift should result in one type of valley form; slow uplift in another. If this proposition holds true, we have a valuable criterion for determining from the form of the river valleys or thalwegs the rate of the uplift to

[1] C. F. Marbut, *Physical Features of Missouri*, p. 104; "Meanders," *Missouri Geological Survey Bull.*, X, 94–109. This is a very excellent discussion of meanders; both the flood plain and incised types.

which a region may have been subjected. In applying this criterion in practice, however, we immediately encounter the difficulty that not all regions have master streams flowing directly to the sea. The region we are studying may be located in the interior of a continent and on a relatively small stream. In such cases, can we use the form of the valley in arriving at conclusions as to the rate of uplift of the region? Obviously not without qualification.

In order to put this criterion on a basis where it may be applied in practice it is only necessary to bear in mind that the equivalent of *uplift* as used in this connection, is *any condition which will cause a stream or any section of a stream to behave as it would if it were independent and subjected to uplift.* In other words the equivalent of uplift may be thought of as any condition which lowers the local base level of a stream. Thus a lowering of the lake level in the case of a stream flowing into a lake or the deepening of a master stream, in the case of a tributary, is equivalent to uplift in an independent stream.

VARYING TYPES OF VALLEY FORM IN DIFFERENT PARTS OF A SINGLE DRAINAGE SYSTEM

Turning our attention once more to our hypothetical drainage system uplifted after having reached the old-age stage of development, we may readily see that, even in this simple case, the same type of valley will not, as a rule, develop in all parts of a drainage system. Take, for example, the case of rapid uplift. We have seen that the master stream would trench rapidly and would form an open valley of type 1 or, where the original course was meandering, the intrenched meander valley of type 2. What would happen meanwhile in the distant headwater branches?

Let the profile of the stream before uplift be represented by the line *a* of Fig. 10. The final profile of equilibrium after uplift may be represented by the line *c*. The trenching resulting from uplift would proceed upstream in such a way that at some time between uplift and final grading the profile would take a form somewhat like the line *b*. Now at a point *W* in its lower course the master stream, at the time represented by the profile *b*, would have cut down a distance represented by the length of the line *V-W*. At another

point, Y, farther up the valley the stream would, in the same time, have cut down a much shorter distance, represented by the line X-Y. The effect at the latter point, particularly on tributaries entering there, would be equivalent to that of a *slow* uplift. We should expect, therefore, to find valleys normal for such an uplift—namely, in-grown meander valleys—developing at that point.

Thus in the lower course of the master stream, valleys typical of a rapid uplift would be found, while in its upper or middle course, and in many of the tributaries, valleys typical of a slow uplift would be encountered.[1]

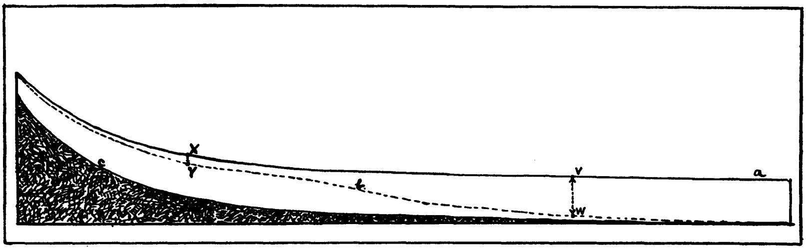

FIG. 10—Diagram to illustrate the explanation of the different types of valleys in different parts of a drainage system. Vertical scale greatly exaggerated.

Valleys of the *in-grown* type are especially likely to develop on the upstream side of resistant rock masses. These resistant masses retard the progress of a wave of trenching following an uplift and the stream above them, which must wait upon their down-cutting, is affected as by a *slow* uplift.

It follows, from considerations outlined above, that, for the *direct* determination of the rate of uplift by means of the form of the stream valleys, only the master streams, or those emptying directly into the sea may be successfully used. In other cases the character of the rocks and the distance from the sea may play a more important part than the rate of uplift. This fact does not, however, destroy the usefulness of the criterion, for it still indicates the rate of lowering of the *local* base-level of any particular stream in question.

[1] A. Penck, in *Morphologie der Erdoberfläche*, Buch II, S. 348, calls attention to the tendency to the formation of meanders in the middle course of a stream; also to the fact that meanders are characteristic of an underloaded stream when it is so placed that it cannot work downward.

Effects of a tilting uplift.—In the above analysis we have considered the drainage system as being uplifted bodily—the mouth of the stream as much as its headwaters. We were led to the conclusion that under those conditions the type of valley in the upper course of a stream would normally be different from that in the lower course.

If the uplift were of a tilting nature with the axis at the mouth of the master stream and with the headwaters receiving the greatest uplift, the upper reaches of the stream would feel the effects of the uplift as soon as any other part of its course, and, if the uplift were rapid, it would seem that the type of valley associated with rapid uplift would prevail throughout.

If we may safely reason from the deductions outlined above, we may conclude that, where rock textures do not complicate matters too much, a drainage system with valleys of the type representing rapid uplift in its lower part, and with types representing slow uplift in its upper branches indicates, though, on account of other complicating factors, it may not prove, a rapid bodily uplift of both headwaters and lower course, while one displaying the forms associated with rapid uplift throughout its course indicates a rapid *tilting* uplift, with maximum elevation in the upper parts of the drainage system. Effects of tilting in the opposite direction need not be considered here: the reader may readily work them out for himself.

If this criterion of tilting is found to hold good it might be possible, in the case of a fairly extensive dendritic drainage system, to determine the axis of tilting by noting the types of valleys in streams coming in from different directions and therefore affected differently by the tilting.

SPECIFIC APPLICATION OF THE CRITERIA.

As an example of the application of the criteria outlined in preceding paragraphs we may take the case of the Mississippi River as illustrated on the Waukon (Iowa-Wis.) sheet. The river here is flowing in a flat-bottomed valley of the open type some two miles wide and with steep, smoothly trimmed and parallel

valley walls some 400 feet in height. The river swings from side to side of the valley in broad, open curves which could scarcely be dignified by the name of meanders.

According to our deductions, an open valley of this type indicates a great predominance of *sweep* over the other processes at work in the formation of the valley. Such a valley might, as we have seen, be brought about by either one of two conditions: (*a*) a rapid deepening of the valley to grade, with subsequent widening, or (*b*) a deepening so slow—perhaps on account of a heavy sediment load—that sweep predominated from the beginning, continually shifting the locus of lateral cutting and thereby widening the valley uniformly as down-cutting proceeded.

In the valley of the Mississippi itself there appears to be nothing to indicate which of these is the correct interpretation, but when the tributary valleys are examined a clue presents itself. They are found (so far as can be judged from the contour maps, which are not so clear as could be desired) to enter through incised meander valleys, most of the larger of them clearly of the *intrenched* type. This form of valley indicates that the local base-level was lowered quickly (the equivalent of rapid uplift), and that the first of the two possible explanations mentioned is more probably the correct one. Such a conclusion should be tested further by the examination of other tributary valleys entering the Mississippi above and below this point. If all the larger tributaries are found to agree in their testimony, the hypothesis of rapid down-cutting by the main stream is strengthened.

The possibility that the valley of the Mississippi, at the point referred to, may, at one time, have carried a glacial stream much larger than the present river, and the fact that the valley is now silted up to a depth of from one to two hundred feet must be taken into consideration, but it does not seem to me to alter essentially the interpretation. Glacial waters may, however, be partly responsible for the remarkable sharpness of the features of the valley walls. In all essential particulars, aside from this sharpness, the valley is similar to that of the Kanawha at Charleston (Fig. 1).

SUMMARY

A study of the form of the immediate valley or thalweg of a large number of streams leads to the recognition of three distinct valley types. These are: (1) the open, comparatively straight and straight-walled valley through which the stream swings in more or less open curves, but in which the curves of the stream do not, except in the very earliest stages, correspond, necessarily, with the curves of the valley as a whole; (2) that form of the incised meander which we may call the intrenched meander, in which the meandering stream has sunk itself with little modification into bed-rock. (In this type undercut bluffs and slip-off slopes are not well developed, though they may be present to some extent. The greater part of the land within the loops retains the original height of the upland); (3) the form of the incised meander which we may designate the *in-grown* meander from the fact that as it sinks itself into the rock it is continually growing so that its final form and size may be very different from that at the beginning of incision. This type of incised meander does not necessitate a particularly meandering course of the stream in the cycle preceding the incision—the meandering course may *develop* as down-cutting proceeds. The valley is characterized by marked undercut bluffs and slip-off slopes. The evidences of growth or expansion during incision are very clearly expressed in the form of the valley.

A valley belonging to any one of these types exhibits a series of characteristic valley forms as it advances in the erosion cycle from the youthful to the mature and old-age stages of development, but there is a strong tendency for the final stages of all the types to become alike.

A large factor in determining the form of the valley, it seems, is the relative rate of down-valley sweep of the river curves. Only when this sweep is subordinate to down-cutting may any form of the incised meander valley be developed.

In a large drainage system rapidly and bodily uplifted, the master streams will normally develop valleys or thalwegs of type 1, the open valley, while in many of the headwater branches valleys of type 3, the in-grown meander, may be the common form.

Any barrier of hard rock in the course of a stream may, by retarding down-cutting, allow the development of valleys of type 3 above the barrier at the same time that below it type 1 is the prevailing form.

In conclusion, it appears that it is the ratio of the rate of vertical down-cutting to that of lateral cutting and sweep which determines the form of the thalwegs. When down-cutting predominates, valleys of types 1 or 2 are formed; when sweep is dominant the open valley, type 1, is the result. It is only when conditions lead to continuous down-cutting so slow that it is equaled or exceeded by lateral cutting, yet rapid enough to make sweep subordinate, that the in-grown meander type of valley may be produced.

These conclusions, if correct, establish valuable criteria for the interpretation of the physical history of a region from the form of its valleys.